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(54) **Increased data communication capacity of a high rate wireless network**

(57)   The invention relates to a wireless radiofrequency data communication system comprising:

• a base-station comprising multiple first sets and a signal processing-unit, wherein each first set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit, wherein the signal processing-unit is connected with each of the first sets for processing signals received by the first sets and processing signals to be transmitted by the first sets, and

• multiple second sets, wherein each second set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit.

FIG. 1

Description

[0001] The invention relates to a wireless radiofrequency data communication system comprising:

- a base-station comprising multiple first sets and a signal processing-unit, wherein each first set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit, wherein the signal processing-unit is connected with each of the first sets for processing signals received by the first sets and processing signals to be transmitted by the first sets, and
- multiple second sets, wherein each second set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit. This system may be a full duplex communication system.
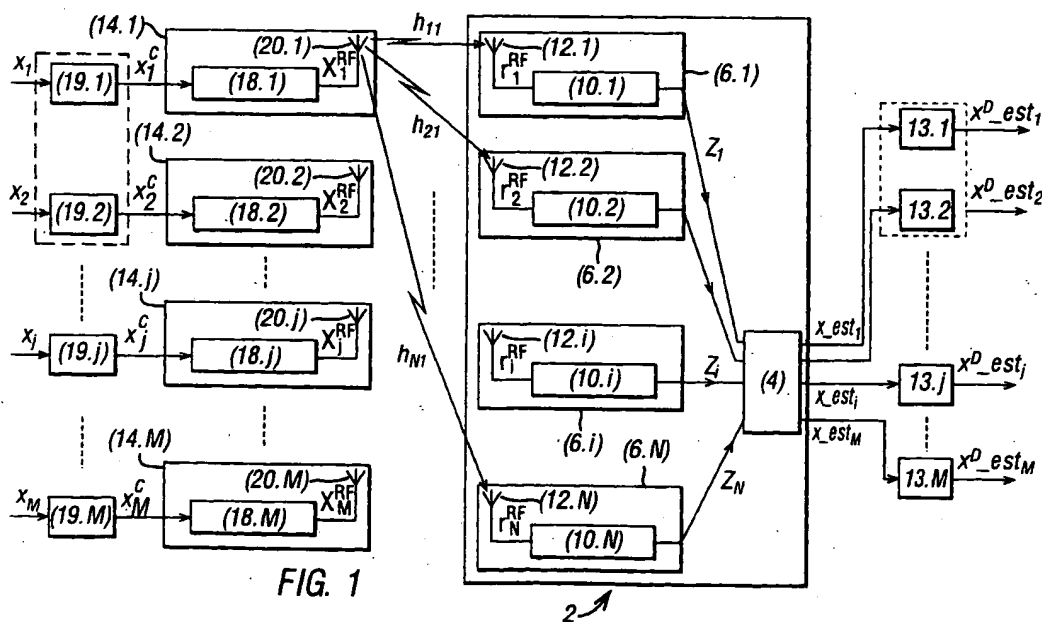
[0002] The invention relates also to a wireless radiofrequency data communication system comprising in use:

- k_1 multiple first groups, wherein each first group comprises a transmitter-unit and at least one antenna which is connected to the transmitter-unit for transmitting a signal; and
- k_2 multiple second groups, wherein each second group comprises a receiver-unit and at least one antenna which is connected to the receiver-unit. This system may be limited to a simplex communication system.

[0003] Wireless radiofrequency data communication systems of this type are known and find their applications in a variety of fields. An example of such an application can be found in the domain of digital communication for electronic-mail. In this application each personal computer can be provided with at least one second set so that the personal computer can be incorporated in an network. The base-station may in that case be connected with a server of the network. Further examples are given, for instance, in the domain of mobile telephony. In the case of mobile telephony the base-station is a telephony exchange. In the majority of the applications more than one second set wants to communicate with the base-station. This means that the second set transmits signals to this base-station and also receives signals from this base-station. Since it would not be acceptable if all second sets would have to wait for each other's communication to be finished, there is a need for simultaneous communication. Simultaneous communication allows more second sets to communicate at the same time with the base-station. A straightforward and common way of realising simultaneous communication is to assign different radiofrequencies to

the respective second sets. In this way all data signals can be separated easily by the first sets in the base-station by frequency selective filters. Furthermore, the base-station can communicate with each second set at the specific radiofrequency which has been assigned to the second set. A transmitted radiofrequency signal contains the actual information to be transmitted to the receiver. This actual information has been modulated on the radiofrequency carrier-signal. Several techniques have been developed for modulating information on the carrier-signal like frequency-modulation, phase-modulation amplitude-modulation et cetera. It is an object of the invention to increase the capacity of the wireless communication system per frequency or frequency-band used by the system.

[0004] The present invention therefore provides in a wireless radiofrequency data communication system which is characterised in that the signal processing-unit comprises information about the transfer-functions of radiofrequency signals from each of the antennas of the first sets to each of the antennas of the second sets and/or vice versa, and wherein the transmitters and receivers, both in the first sets and in the second sets, operate on essentially the same radiofrequency or radiofrequency-band, and wherein the signal processing-unit processes the signals received by the first sets and processes the signals to be transmitted by the first sets on the basis of said transfer functions such that for each second set of a plurality of the second sets an individual communication channel is formed with the base-station wherein these communication channels are generated simultaneously and separately from each other.

[0005] In this manner multiple communication channels are realised on the same frequency, or within the same frequency-band, based on the principle that the signals can be separated thanks to the different characteristics of the transfer-functions. Hence the capacity per frequency or frequency-band is indeed increased. The geometry of the configuration of the communication system determines the transfer functions which belong to the different travel-paths between the antennas of the first sets and the second sets in the base-station. These transfer functions are expressed by complex numbers. Each complex number expresses the transfer function between one antenna of one of the first sets and one antenna of the second set. The amplitude of the complex number is the attenuation of the signal's strength and the phase of the complex number is the phase modulation incurred during transmission along the travel-path. Since the used frequencies are relatively high, the transfer functions depend largely on the configuration. The system according to the present invention can be used as a full duplex communication system.

[0006] A special embodiment according to the invention is characterised in that the number of first sets is N and, in use, the number of second sets is M, wherein N is greater than M, wherein the signal processing-unit is provided with an inputport for imputing M signals to be

received by the respective M second sets, wherein the processing unit is arranged to process the M signals in combination on the basis of the information of the transfer-functions to obtain N transmit-signals which are fed to the respective N first sets for being transmitted by the first sets to the second sets and wherein the processing unit is arranged to process the M signals in combination in such a way that the M signals are received separately by the respective M second sets if the second sets each receive the N transmit-signals, thereby establishing M of said simultaneous communication channels. According to this special embodiment transmission of data-signals to the respective second sets can be performed in a very accurate way. Preferably this embodiment is further characterised in that
the processing unit is arranged to, in use, process, on the basis of the information about the transfer-functions H, the M signals Q to obtain the N transmit-signals R, to be transmitted by the first sets, according to

$$R = P_D \, Q, \qquad (I)$$

resulting in that the M signals Q are received separately by the respective second sets if the second sets each receive the N transmit-signals, where $P_D = [H^* \, (H^* H)^{-1}]^T$ is the pseudo-inverse for H^T and where H^* is the complex conjugated and transposed of H, wherein H is a complex [N * M] matrix containing transfer functions h_{ij} (i=1,...,N; j=1,...,M), wherein h_{ij} is the transfer function for transmission from the jth second set of the M second sets to the ith first set of the N first sets, and where Q is a complex M dimensional vector $[Q_1, Q_2,...,Q_j,...,Q_M]^T$ wherein Q_j is the signal to be transmitted to the jth second set of the M second sets and where $R= [R_1, R_2,..., R_i,...,R_N]^T$ wherein R_i is the transmit-signal to be transmitted by the ith first set of the N first sets.

[0007] A further embodiment according to the invention is characterised in that the number of first sets is N and, in use, the number of second sets is M, wherein N is greater than M, wherein, in use, each of the M second sets transmits a signal so that M signals are transmitted to be received in combination by the first sets wherein the signal processing-unit is arranged to process in combination signals received by each of the first sets on the basis of the information about the transfer-functions to recover the M signals transmitted by the M second sets separately from each other, thereby obtaining M of said simultaneous communication channels. According to this embodiment M signals can be transmitted from the respective second sets to be individually recovered by the base-station in a very accurate way. Preferably this embodiment is further characterised in that the processing unit is arranged to, in use, process, on the basis of the information about the transfer-functions H, the signals r which are received by the first sets, to calculate an estimation x_est of the M signals x^c which

were transmitted by the M second sets, according to the mathematical expression

$$x\_est = P_U \, r, \qquad (II)$$

where $P_U = [(H^* H)^{-1} H^*]$ is the pseudo-inverse for H and where H^* is the complex conjugated and transposed of H, wherein H is a complex [N * M] matrix containing transfer functions h_{ij} (i=1,...,N; j=1,...,M), wherein h_{ij} is the transfer function for transmission from the jth second set of the M second sets to the ith first set of the N first sets, r is a complex N dimensional vector $[r_1,..., r_i,...,r_N]^T$ with r_i the signal received by the ith first set of the N first sets, x_est is a complex M dimensional vector $[x\_est_1,...,x\_est_j,...,x\_est_M]^T$ where x_est_j is an estimation of x^c_j, and where x^c is a complex M-dimensional vector $[x^c_1,...,x^c_j,...x^c_M]^T$, with x^c_j being the signal transmitted by the jth second set of the M second sets. Equation (II) is based on the model (III)

$$r = H \, x^c + n, \qquad (III)$$

where n is a complex N-dimensional vector containing noise terms picked up during reception.

[0008] Additionally, in this embodiment of the invention, the base-station can, according to equation (II), suppress noise in the signals which are transmitted by the second sets. This is of importance since mostly the second sets will comprise mobile transmitters which are not able to transmit high-power signals. The base-station on the other hand will possess enough power to transmit signals with a relative high amplitude, noise reduction at the side of the second sets is therefore of less importance.

[0009] Depending on the travel-path and the specific radiofrequency used, the transmitted signal may suffer from fading. This can be rather serious, even resulting in that such a signal may lack the strength to be properly received. Knowledge of the transfer-functions can serve in preventing the use of those frequencies which suffer too much from fading for a particular travel-path.

[0010] An advantageous embodiment of the data communication system according to the invention is characterised in that each second set comprises a serial-to-parallel/parallel-to-serial unit, which unit, in use, splits the data signal of said second set in a multiple of signals, and means for modulating these signals on different frequencies according to the Inverse Fast Fourier Transformation, and wherein each first set comprises a unit for executing a Fast Fourier Transformation on the signal received by said first set and means for combining the transformed signals in order to recover said data-signal. This is the concept of the Orthogonal Frequency Division Multiplexing (OFDM) technique. The OFDM technique can be applied for preventing Inter-Symbol In-

terference (ISI). The ISI effect is the effect wherein symbols interfere with each other as a consequence of differences in travel-path lengths, for instance caused by the multipath phenomenon. This can be illustrated with the following example: At a symbol rate of say 10 [Mega-symbols/second] and a maximum delay spread of say 100 [ns] each symbol smears out over two symbol intervals, resulting in a significant amount of ISI. This ISI effect may be prevented by cyclically extending the symbol interval with a guard interval which is larger than the delay spread. The OFDM technique has in the system according to the invention as a further advantage that the effects of frequency selective fading are strongly reduced. Delay spread causes different attenuations for the N different signals r received by the first sets. Some of the received signals r_i may be in a deep fade, thereby degrading the overall bit error probability. The conventional approach to fix this problem is to apply forward error correction coding accross the received signals r_i, such that a few erroneous received signals r_i can be corrected. With the present multi-antenna processing, the probability of deep fades is greatly reduced because of the antenna receiving diversity effect. Hence the combination of multi-antenna processing and OFDM also reduces or eliminates the problem of frequency selective fading. In short: The combination of multi-antenna processing according to the present invention and OFDM for each signal which is transmitted by the second set 14.j has the advantages that ISI is avoided and that no or less coding redundancy is required compared to a single antenna OFDM system. Hence the application of OFDM will considerable limit the number of erroneous signals. This is of special interest for the data communication capacity since signals which have not been received correctly, which will be detected with a redundancy check, have to be transmitted again. This will cost a lot of overhead according according to the communication protocol and will reduce the overall data communication capacity.

[0011] Yet the system of the invention which may be limited to a simplex communication system is a wireless radiofrequency data communication system comprising in use:

- k_1 multiple first groups, wherein each first group comprises a transmitter-unit and at least one antenna which is connected to the transmitter-unit for transmitting a signal; and
- k_2 multiple second groups, wherein each second group comprises a receiver-unit and at least one antenna which is connected to the receiver-unit, characterised in that, the wireless radiofrequency data communication system further comprises a signal processing-unit which is, if $k_1 > k_2$, connected to each of, the first groups and which is, if $k_1 < k_2$, connected to each of, the second groups, wherein the signal processing-unit comprises information about the transfer-functions of radiofrequency signals

from each of the first groups to each of the second groups and/or vice versa, and wherein, each of the transmitter-units, of the first groups operates on essentially the same radiofrequency or radiofrequency band, and wherein, in use, if $k_1 > k_2$, the signal processing-unit processes k_2 data-signals to be transmitted to the k_2 second groups for obtaining k_1 signals which are supplied to the respective first groups to be transmitted, wherein the k_2 data signals are processed on the basis of said transfer functions in such a manner that the respective second groups will receive separately the respective k_2 data-signals, thereby establishing k_2 simultaneous communication channels, and wherein, in use, if $k_1 < k_2$, the signal processing-unit processes k_2 signals, which are received by the respective second groups on the basis of said transfer functions in such way that an estimation is made of the k_1 signals transmitted by the first groups, thereby establishing k_1 simultaneous communication channels. Additionally, this overall data communication system can also be carried out with the concept of the so-called Orthogonal Frequency Division Multiplexing (OFDM) method.

[0012] In the accompanying drawings, in which certain modes of carrying out the present invention are shown for illustrative purposes:

Figure 1 is a diagram showing a wireless data communication system operating at one specific radiofrequency in the uplink situation;
Figure 2 is a diagram showing a wireless data communication system operating at one specific radiofrequency in the downlink situation;
Figure 3 is a diagram showing a wireless data communication system which operates on a frequency-band.

[0013] An embodiment of a wireless radiofrequency data communication system according to the invention is shown in figure 1. This wireless radiofrequency data communication system comprises a base-station 2 which comprises a signal processing-unit 4 and multiple first sets 6.i (i=1,2,...,N). Each first set 6.i comprises a transmitter- and receiver-unit 10.i, comprising a transmitter and a receiver, and at least one antenna 12.i which is connected to the transmitter- and receiver-unit 10.i. In this example each first set 6.i comprises one antenna 12.i connected to the transmitter- and receiver-unit 10.i. The signal processing-unit 4 is at one side connected to each of the first sets 6.i, i=1,2,...,N, and at another side connected to each of the coding/decoding-units 13.j, j=1,2,...,M. Furthermore, the system comprises multiple second sets 14.j (j=1,2,...,M), wherein each second set 14.j comprises a transmitter- and receiver-unit 18.j and at least one antenna 20.j which is connected to said transmit- and receive unit 18.j. Each of the

second sets 14.j is connected with a coding/decoding-unit 19.j, j=1,2,...,M.

[0014]   The first sets 6.i in the base-station 2 can transmit and receive signals to/from the second sets 14.j. The situation wherein signals are transmitted from the second sets 14.j to the first sets 6.i in the base-station 2 is called uplink, this is the situation depicted in figure 1. Transmission of signals from the first sets 6.i in the base-station 2 to the second sets 14.j is called downlink, this is illustrated in figure 2. In the configurations of figure 1 and figure 2 there are N first sets 6.i in the base-station 2 and, in use, M second sets 14.j. (The number M of second sets 14.j which are actually used may vary). Hereby it is possible that each second set 14.j belongs to one user, but it is equally possible that one user uses more than one second set 14.j. It is even thinkable that one user uses all second sets. Mostly the base-station will be connected to a server, for instance an internet and/or intranet server for establishing wireless connections with and between mobile notebooks. Each of these mobile notebooks is provided with at least one second set.

[0015]   In the uplink situation (figure 1) a radiofrequency transmission signal x^{RF}_j is generated by the second set 14.j and subsequently transmitted to the first sets 6.i (i=1,..,N). Each signal x^{RF}_j contains the modulated information of data-signal x_j. The data-signal x_j is the input to the coding/decoding unit 19.j, the output of this unit is the low-frequency signal x^c_j. The first function in the uplink situation of the coding/decoding unit 19.j is to modulate data-signal x_j on a carrier-signal, which yields the low-frequency signal x^c_j. (Examples of methods of modulation are amplitude modulation and phase modulation. These kinds of modulation are known). A possible second function of the coding/decoding unit 19.j is to apply Forward Error Correction. (The technique of Forward Error Correction is known). Moreover, if desired, some of the coding/decoding units 19.j can be combined into a single coding/decoding unit. This is schematically indicated in figure 1 with the dotted line which combines the units 19.1 and 19.2). The transmitter- and receiver-unit 18.j, which comprises a radiofrequency-modulation and a radiofequency-demodulation function, modulates the output x^c_j of the coding/decoding unit 19.j on a radiofrequency-carrier signal which leads the radiofrequency transmission signal x^{RF}_j. The signals x^{RF}_j (j=1,..,M) are transmitted simultaneously by the second sets 14.j to all first sets 6.i (i=1,...,N). As a consequence of this, each of the first sets 6.i receives a radiofrequency signal r^{RF}_i. This signal r^{RF}_i is in fact a combination of the transmitted signals. In each of the transmitter- and receiver units 10.i of the first sets 6.i the first step is the removal of the carrier frequency (which is radiofrequency-demodulation by the transmitter- receiver-unit 10.i) this yields the low frequency signals r_i, i=1,2,...,N. Then, each signal r_i is passed to the signal processing-unit 4. The signal processing-unit receives N input signals r_i and generates M output signals x_est_j.

The operation of the signal processing-unit will be described later. The N input signals r_i and the M output signals x_est_j of the signal processing unit 4 can be analogue as well as digital. In this example these signals are analogue low frequency signals. The signal x_est_j is fed to the coding/decoding unit 13.j (j=1,2,...,M), which unit has as a main function to perform demodulation of the signal x_est_j, yielding the information-signal $x^D\_est_j$ in bits form. The signal $x^D\_est_j$ is equal, or approximately equal, to x_j. A possible function of the coding/decoding units 13.j and 19.j is the application of Forward Error Correction. It is also noted here that, if desired, some of the units 13.j can be combined in a single unit. This is illustrated schematically for coding/decoding units 13.1 and 13.2 in figure 1 with the dotted line.

[0016]   In the downlink situation (figure 2), firstly each of the coding/decoding units 13.j (j=1,2,...,M) gets an input data-signal q_j (j=1,2,...,M). This data-signal q_j contains the information to be transmitted in the form of bits. (The signals q_j are the respective data-signals to be transmitted to the respective second sets 14.j (j=1,2,..., M)). Next, the input-signal q_j is modulated into a low frequency signal Q_j by the coding/decoding unit 13.j. The signal processing unit 4 generates N output signals R_i (i=1,...,N) on the basis of these M low frequency signals Q_j, j=1,...M. The signals R_i are passed to the first sets 6.i and more specifically to the transmitter- and receiver-units 10.i of these first sets 6.i. These transmitter- and receiver-units generate the radiofrequency transmission signals Z^{RF}_i (i=1,..,N), which signals are transmitted to the second sets 14.j. Antenna 20.j of each second set 14.j receives a signal X^{RF}_1, which signal is in fact a combination of the transmitted signals. This signal is radiofequency-demodulated by the transmitter- and receiver-unit 18.j (j=1,2,...,M), which means that the radiofrequency-carrier signal is removed from the signal X^{RF}_j. The low-frequency output signal X_j of the transmitter- and receiver-unit 18.j is the input signal of the coding/decoding unit 19.j (j=1,2,...,M). The coding/decoding unit 19.j demodulates the signal X_j which yields the data signal X^D_j (in bits) which is equal (or approximately equal) to q_j (j=1,2,...,M).

[0017]   In the uplink situation (figure 1) radiofrequency signals x^{RF}_j may travel along a selection of so-called travel-paths $T_{i,j}$, i=1,2,...,N; j=1,2,...,M. The travel-path $T_{i,j}$ is defined as the travel-path between the antenna 12.i and the antenna 20.j. Since all signals x^{RF}_j are transmitted on essentially the same frequency, for each travel-path $T_{i,j}$ a transfer-function can be defined which is expressed in a complex number h_{ij}. The amplitude of this complex number h_{ij} is the attenuation of the transmitted signal and the phase of this complex number h_{ij} is the phase distortion of the transmitted signal during transmission from the antenna 20.j to the antenna 12.i and vice versa. All elements h_{ij} (i=1,...,N; j=1,...,M) are stored in a [N*M] matrix H. This matrix H is called the transfer-function. The transfer-function H is important since the information, which is modulated on a radiofre-

quency signal by phase and/or amplitude modulation, can accurately be recovered if the receiver can correct for the amplitude and/or phase distortion which has occured during transmission. It is supposed that the transfer function **H** is known by the signal processing-unit 4. The transfer-function has to be measured regularly by the data communication system. Below, the use of the transfer-function **H** and the procedure (which is known per se) of measuring the transfer-function is elucidated. The transfer function for downlink is the transposed of the transfer function for uplink. So, if the transfer function for uplink is known then the transfer function for downlink is known also.

[0018] The initiation of the calculation (or calibration) of the transfer-functions can be controlled by the signal processing-unit 4. In a particular algorithm all antennas (of the first and second sets) but one antenna 20.j of one second set 14.j are forced to be silent, wherein the one antenna 20.j transmits a calibration signal to the antennas 12.i of the first sets 6.i. The signal which is received by the first set 6.i is a measure for the transfer function h_{ij} (i=1,2,...,N). This procedure can be repeated for all other antennas of the second sets. Afterwards the transfer-functions are known by combining the information gathered in this manner. Since the used frequencies are relatively high, the transfer-functions depend largely on the configuration. This implicates that the transfer-functions have to be updated with a fairly high rate.

[0019] According to the invention multiple simultaneous communication channels may be generated on essentially one radiofrequency, both for uplink and downlink, between the first sets 6.i of the base-station 2 and the second sets 14.j. For this, use is made of the knowledge the transfer-function **H**. The generation of multiple simultaneous communication channels significantly increases the data transmission capacity of the wireless data communication system relative to other systems using the same frequency. The generation of simultaneous communication channels will be explained in detail below, first for the uplink situation and then for the downlink situation. All necessary calculations are performed by the signal processing-unit 4, which is in this particular embodiment situated in the base-station 2.

[0020] Now the role of the signal processing unit 4 in the uplink situation (figure 1) will be explained in more detail. In the uplink situation the signal processing unit 4 establishes M simultaneous communication channels. This is accomplished as follows: The coding/decoding unit 19.j provides the second sets 14.j with low-frequency signals x^c_j on the basis of the data-signals x_j. (This is done for all second sets j=1,...,M). These signals have to be transmitted to the base-station. Therefore, the respective M second sets 14.j transmit the respective M radiofrequency data signals x^{RF}_j (j=1,2,...,M), containing the respective coded information of data signals x_j, simultaneously to the N first sets 6.i (i=1,2,...,N). Next, the first sets 6.i (i=1,...,N) generate the signals r_i (i=1,2,..., N). (The ith first set of the N first sets generates

signal r_i). The signal processing unit receives N input signals r_i which may be noted as a N-dimensional vector $r=[r_1,...,r_N]^T$. On the basis of these input signals, the signal processing-unit calculates estimation signals for the signals x^c_j according to an estimation algorithm. The output of the signal processing-unit are these estimation signals x_est$_j$ (j=1,2,...,M) which may be noted as a M-dimensional vector x_est=[x_est$_1$...x_est$_M$]^T.

[0021] During transmission and reception noise will be picked up by the reception signals r^{RF}_i, this noise will accumulate in a noise term n_i in r_i. These noise terms may be noted as a N-dimensional vector $n=[n_1... n_N]^T$. Since N>M the signals **x** can be recovered by the estimation algorithm. This estimation algorithm is based on the mathematical model **(IV)**.

$$r = H x^c + n, \qquad (IV)$$

[0022] where **H** is a complex [N*M] matrix containing the transfer functions h_{ij} for uplink. The vector x^c is a M dimensional vector $x^c = [x^c_1, x^c_2,...,x^c_j,...,x^c_M]^T$ where x^c_j is the low frequency signal which is transmitted by the second set 14.j. Note that the low-frequency signal x^c_j actually has to be modulated on a radiofrequency carrier for being able to be transmitted by the second sets, this modulation leads the signal x^{RF}_j. Each component of x^c is one communication channel. The signal processing-unit calculates the M-dimensional estimation vector x_est of the transmitted signal x^c according to the mathematical least-squares estimation based on formula **(V)**

$$x\_est = P_U\ r, \qquad (V)$$

[0023] where $P_U = [(H^* H)^{-1} H^*]$ is the pseudo-inverse for **H** and where **H*** is the complex conjugated and transposed of **H**. In this way, according to **(V)**, M simultaneous communication channels for uplink are obtained. The estimation algorithm also brings along a valuable effect of noise suppression because the noise contribution in r_i can be quite serious since the second sets will not always dispose of powerful transmitters.

[0024] Now the role of the processing unit 4 in the downlink situation will be elucidated. In the downlink situation (figure 2) the input of the signal processing-unit is fed with the M low frequency signals Q_j. As will be explained, each of the signals Q_j is a communication channel. The low-frequency signals Q_j may be noted as a M-dimensional vector $Q=[Q_1,...,Q_M]^T$. In the downlink situation M simultaneous communication channels are generated by the signal processing unit 4 in the following way. On the basis of **Q** the signal processing-unit generates the N output signals R_i (i=1,...,N) which may be noted as a N-dimensional vector $R= [R_1...R_N]^T$. Note that the low-frequency signal R_i actually has to be modulated on a radiofrequency carrier for being able to be

transmitted by the first sets, this modulation leads the signal Z^{RF}_j. During reception in the first sets 14.j (j=1,..., M) the received signal X^{RF}_j will be incurred with noise. The noise contribution in the received signal X_j is noted as E_j (j=1,2,...,M). A noise vector may be noted as follows $E = [E_1...E_M]^T$. The signal processing-unit 4 calculates such a signal R that the signals X_j in the second sets 14.j are equal (or approximately equal in case of noise) to the respective low-frequency signals Q_j (j=1,2,...,M). This procedure is elaborated with the following mathematical expression:

$$R = P_D Q \qquad (VI)$$

[0025]   In (VI) the signal R is expressed in terms of the low-frequency signal Q, wherein $P_D = [H^* (H^* H)^{-1}]^T$ is the pseudo-inverse for H^T, and where H^* is the complex conjugated and transposed of H, wherein H is a complex [N * M] matrix containing the transfer functions h_{ij} for transmission from the second sets to the first sets. The signal X, which is a M-dimensional vector $[X_1,...,X_M]$, is the output of the second sets and is given by

$$X = H^T P_D Q + E = Q + E \qquad (VII)$$

where H^T is the transfer function for downlink (since H is the transfer function for uplink). So, indeed M simultaneous communication channels for downlink are obtained if the signal processing-unit converts the low-frequency signals Q into the signals R according to (VI).

[0026]   The wireless data communication system as described hereinbefore operates on just one frequency, thereby using multiple simultaneous communication channels (in a duplex mode) at this frequency for increasing the communication capacity. This concept can be exploited at a greater extend by using a system according to the invention which operates at a frequency-band. This concept is particularly suited for being used in combination with the Orthogonal Frequency Division Multiplexing (OFDM) method. The OFDM method, which is known per se, is applied in practice for preventing the transmitted symbols from Inter-Symbol Interference (ISI) effects and for reducing fading effects which occur, strongly dependant of the used radiofrequency, during transmission. The multi-antenna processing technique combined with the OFDM technique (explained below) yields two important advantages. The first advantage of OFDM is that the Inter-Symbol Interference (ISI) is significantly reduced. ISI is the effect wherein symbols interfere with each other as a consequence of differences in travel-path lengths, for instance caused by the multipath phenomenon. According to the OFDM method a single data signal is splitted in multiple signals with a lower data rate, due to this lower data rate the risk of said interference is reduced. The second ad-

vantage of OFDM is that the effects of frequency selective fading are strongly reduced. Delay spread causes different attenuations for the N different signals r received by the first sets. Some of the received signals r_i may be in a deep fade, thereby degrading the overall bit error probability. The conventional approach to fix this problem is to apply forward error correction coding across the received signals r_i, such that a few erroneous received signals r_i can be corrected. With the present multi-antenna processing, the probability of deep fades is greatly reduced because of the antenna receiving diversity effect. Hence the combination of multi-antenna processing and OFDM also reduces or eliminates the problem of narrowband fading.

[0027]   The principle of using a frequency-band in combination with OFDM will now be described for the uplink situation as is shown in figure 3. In figure 3 the geometry of the first sets 6.i lodged in the base-station 2, the second sets 14.j, the coding/decoding units 13.j and 19.j, the transmitter- and receiver-units 18.j and 10.i are all comparable with the embodiments of figures 1 and 2. In the figures 1-3 similar elements have been indicated with the same reference numbers. The input to the coding/decoding unit 19.j (j=1,..,M) is the data-signal S_j, this signal contains the information (for example in bits) which has to be transmitted to the first sets 6.i (i=1,...,N) in the base station 2. The output of the coding/decoding unit 19.j is the low-frequency signal S^c_j (j=,....,M). The second sets 14.j in figure 3 also comprise a serial-to-parallel/parallel-to-serial unit 21.j. The input for this unit is the low frequency signal S^c_j. In the serial-to-parallel/parallel-to-serial unit 21.j the signal S^c_j is splitted in K signals $[s_{j1},..., s_{jK}]$. Furthermore, the second set 14.j comprises a Fast-Fourier-Transform/ Inverse-Fast-Fourier-Transform (FFT/IFFT) unit 22.j. In the uplink situation the unit 22.j receives said K signals at its input and performs an Inverse Fast Fourier Transformation yielding a signal comprising K different frequencies. This signal is fed to the transmitter- and receiver-unit 18.j for transmission of a narrow-band transmission radiofrequency signal S^{RF}_j (j=1,2,...,M) to be received by the first sets 6.i (i=1,2,..., M). The received signals of the first sets 6.i are noted by V^{RF}_i (i=1,2,...,N). The transmit- and receive-units 10.i of the first sets 6.i each remove the radiofrequency carrier from the received signals V^{RF}_i to obtain (low frequency) signals V^c_i (i=1,2,...,N). The first sets 6.i each comprise a Fast-Fourier-Transform/Inverse-Fast-Fourier-Transform (FFT/IFFT) unit 24.i. In the uplink situation this unit receives the input signal V^c_i which comprises, in principle, K different frequencies, the output comprises K separate low-frequency signals $[v_{i1},...,v_{iK}]$. The signal processing unit 4 processes the K*N output-signals v_{ik} (i=1,2,...,N; k=1,2,...,K) of the FFT/IFFT units 24.i (i=1,..., N). For this, the signal processing unit 4 comprises two types of units: The least squares estimation units 4A.k, k=1,...,K and the serial-to-parallel/parallel-to-serial units 4B.j, j=1,...,M. The least squares units 4A.k are each analogous to the "single-frequency signal processing

unit" 4 in figures 1 and 2. Each least squares unit 4A.k receives N input signals v_{ik} (i=1,2,...,N) from the first sets 6.i. The output of each unit 4A.k consists of M estimation signals. These estimation signals are combined is such a way that the output signal of the jth serial-to-parallel/ parallel-to-serial unit 4B.j is given by S_est_j= (s_est_{j1},..., s_est_{jK}], where s_est_{jk} is an estimation signal for s^c_{jk}. Finally, the low-frequency signal S_est_j is demodulated by the coding/decoding unit 13.j, which yields the signal $S^D\_est_j$. The signal $S^D\_est_j$ is equal, or approximately equal, to S_j, j=1,..,M. So, the wireless data communication system of figure 3 comprises M simultaneous communication channels at each of the K frequencies, wherein information is transmitted in parallel.

[0028] The wireless data communication system of figure 3 can also be used for downlink. In that case all arrows shown in figure 3 have to be reversed in an analogous way as has been carried out in figure 2 with respect to figure 1. So, also for downlink, use can be made of a frequency-band in combination of OFDM.

[0029] In accordance with the provisions of the patent statutes, the present invention has been described in what is considered to represent its preferred embodiments. However, it should be noted that the invention can be practised otherwise than as specifically illustrated and described without departing from its spirit or scope. For instance, it is thinkable that one uses not only one wireless data communication systems (comparable with the one described in figures 1, 2) but a multiple of these systems for being able to operate on a frequency-band instead of just one frequency. A special, very efficient, example of such a system is the embodiment of the system described in figure 3. Moreover, for systems which operate on a frequency-band it is thinkable that these systems dispose over an algorithm for establishing radiofrequencies for which the signal has the least attenuation for a specific travel-path. It is then preferable to transmit on these frequencies. Furthermore, it is clear that the described systems can be used by one or by more than one user. If the system is used by just one user, then this user can dispose over a very high communication capacity. Mostly, the increased system capacity will be used to serve multiple users, with the possibility that some user(s) dispose over more than one antenna and/or sets.

[0030] Furthermore, the system according to the figures 1-3 can also be reduced to a simplex communication system. For example the transmitter- and receiver-units 10.i may be replaced by transmit-units (i=1,2,...,N) and the transmitter-and receiver-units 18.j may be replaced by receive-units 18.j (j=1,2,...,M). If N=k_1 and M=k_2 with $k_1 > k_2$ the first sets 6.i are first groups 6.i for transmission only and the second sets 14.j are second groups 14.j for receiving only. Hence M=k_2 simplex communication channels are formed. Alternatively, the transmitter- and receiver-units 10.i may be replaced by receiver-units 10.i (i=1,2,...,N) and the transmitter- and receiver-units 18.j may be replaced by transmitter-units

18.j (j=1,...,M). If N=k_2 and M=k_1 with $k_1<k_2$ the first sets 6.i are second groups 6.i for receiving only and the second sets 16.j are first groups 16.j for transmission only (j=1,2,...,M). Hence M=k_1 simplex communication channels are formed. Each of the above systems can also be combined with the OFDM techniques as discussed in relation with figure 3.

Claims

1. Wireless radiofrequency data communication system comprising:

   • a base-station comprising multiple first sets and a signal processing-unit, wherein each first set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit, wherein the signal processing-unit is connected with each of the first sets for processing signals received by the first sets and processing signals to be transmitted by the first sets, and

   • multiple second sets, wherein each second set comprises a transmitter- and receiver-unit provided with a transmitter and a receiver and at least one antenna which is connected to the transmitter- and receiver-unit, **characterised in that**, the signal processing-unit comprises information about the transfer-functions of radiofrequency signals from each of the antennas of the first sets to each of the antennas of the second sets and/or vice versa, and wherein the transmitters and receivers, both in the first sets and in the second sets, operate on essentially the same radiofrequency or radiofrequency-band, and wherein the signal processing-unit processes the signals received by the first sets and processes the signals to be transmitted by the first sets on the basis of said transfer functions such that for each second set of a plurality of the second sets an individual communication channel is formed with the base-station wherein these communication channels are generated simultaneously and separately from each other.

2. Wireless radiofrequency data communication system according to claim 1, **characterised in that**, the communication channels are duplex communication channels.

3. Wireless radiofrequency data communication system according to claim 1 or 2, **characterised in that**, the number of first sets is N and, in use, the number of second sets is M, wherein N is greater than M, wherein the signal processing-unit is pro-

vided with an inputport for imputing M signals to be received by the respective M second sets, wherein the processing unit is arranged to process the M signals in combination on the basis of the information of the transfer-functions to obtain N transmit-signals which are fed to the respective N first sets for being transmitted by the first sets to the second sets and wherein the processing unit is arranged to process the M signals in combination in such a way that the M signals are received separately by the respective M second sets if the second sets each receive the N transmit-signals, thereby establishing M of said simultaneous communication channels.

4. Wireless radiofrequency data communication system according to claim 3, **characterised in that**, the processing unit is arranged to, in use, process, on the basis of the information about the transfer-functions **H**, the M signals **Q** to obtain the N transmit-signals **R**, to be transmitted by the first sets, according to

$$R = P_D\ Q, \qquad (A)$$

resulting in that the M signals **Q** are received separately by the respective second sets if the second sets each receive the N transmit-signals, where $P_D = [H^*\ (H^*\ H)^{-1}]^T$ is the pseudo-inverse for H^T and where H^* is the complex conjugated and transposed of **H**, wherein **H** is a complex [N * M] matrix containing transfer functions h_{ij} (i=1,...,N; j=1,...,M), wherein h_{ij} is the transfer function for transmission from the jth second set of the M second sets to the ith first set of the N first sets, and where **Q** is a complex M dimensional vector $[Q_1, Q_2, ..,Q_j,..., Q_M]^T$ wherein Q_j is the signal to be transmitted to the jth second set of the M second sets and where $R= [R_1, R_2,...,R_i,...,R_N]^T$ wherein R_i is the transmit-signal to be transmitted by the ith first set of the N first sets.

5. Wireless radiofrequency data communication system according to any preceding claim, **characterised in that**, the number of first sets is N and, in use, the number of second sets is M, wherein N is greater than M, wherein, in use, each of the M second sets transmits a signal so that M signals are transmitted to be received in combination by the first sets wherein the signal processing-unit is arranged to process in combination signals received by each of the first sets on the basis of the information about the transfer-functions to recover the M signals transmitted by the M second sets separately from each other, thereby obtaining M of said simultaneous communication channels.

6. Wireless radiofrequency data communication sys-

tem according to claim 5, **characterised in that**, the processing unit is arranged to, in use, process, on the basis of the information about the transfer-functions **H**, the signals **r** which are received by the first sets, to calculate an estimation **x_est** of the M signals x^c which were transmitted by the M second sets, according to the mathematical expression

$$x\_est = P_U\ r, \qquad (B)$$

where $P_U = [\ (H^*\ H)^{-1}\ H^*\ ]$ is the pseudo-inverse for **H** and where H^* is the complex conjugated and transposed of **H**, wherein **H** is a complex [N * M] matrix containing transfer functions h_{ij} (i=1,...,N; j=1,...,M), wherein h_{ij} is the transfer function for transmission from the jth second set of the M second sets to the ith first set of the N first sets, **r** is a complex N dimensional vector $[r_1,..., r_i,..., r_N]^T$ with r_i the signal received by the ith first set of the N first sets, **x_est** is a complex M dimensional vector $[x\_est_1,..., x\_est_j,...,x\_est_M]^T$ where x_est_j is an estimation of x^c_j, and where x^c is a complex M-dimensional vector $[x^c_1,...,x^c_j,...x^c_M]^T$, with x^c_j being the signal transmitted by the jth second set of the M second sets.

7. Wireless radiofrequency data communication system according to claim 6, **characterised in that** each second set comprises a serial-to-parallel/parallel-to-serial unit, which unit, in use, splits the data signal of said second set in a multiple of signals, and means for modulating these signals on different frequencies according to the Inverse Fast Fourier Transformation, and wherein each first set comprises a unit for executing a Fast Fourier Transformation on the signals received by said first set and means for combining the transformed signals in order to recover said data-signal.

8. Wireless radiofrequency data communication system comprising in use:

   • k_1 multiple first groups, wherein each first group comprises a transmitter-unit and at least one antenna which is connected to the transmitter-unit for transmitting a signal; and
   • k_2 multiple second groups, wherein each second group comprises a receiver-unit and at least one antenna which is connected to the receiver-unit, **characterised in that**, the wireless radiofrequency data communication system further comprises a signal processing-unit which is, if $k_1 > k_2$, connected to each of, the first groups and which is, if $k_1 < k_2$, connected to each of, the second groups, wherein the signal processing-unit comprises information about the transfer-functions of radiofrequency

signals from each of the first groups to each of the second groups and/or vice versa, and wherein, each of the transmitter-units, of the first groups operates on essentially the same radiofrequency or radiofrequency band, and wherein, in use, if $k_1 > k_2$, the signal processing-unit processes k_2 data-signals to be transmitted to the k_2 second groups for obtaining k_1 signals which are supplied to the respective first groups to be transmitted, wherein the k_2 data signals are processed on the basis of said transfer functions in such a manner that the respective second groups will receive separately the respective k_2 data-signals, thereby establishing k_2 simultaneous communication channels, and wherein, in use, if $k_1 < k_2$, the signal processing-unit processes k_2 signals, which are received by the respective second groups on the basis of said transfer functions in such way that an estimation is made of the k_1 signals transmitted by the first groups, thereby establishing k_1 simultaneous communication channels.

9. Wireless radiofrequency data communication system according to claim 8, **characterised in that** each first group comprises a serial-to-parallel/parallel-to-serial unit, which unit, in use, splits the data signal in a multiple of signals, and means for modulating these signals on different frequencies according to the Inverse Fast Fourier Transformation, and wherein each second group comprises a unit for executing a Fast Fourier Transformation on the signals received by said second group and means for combining the transformed signals in order to recover said data-signal.
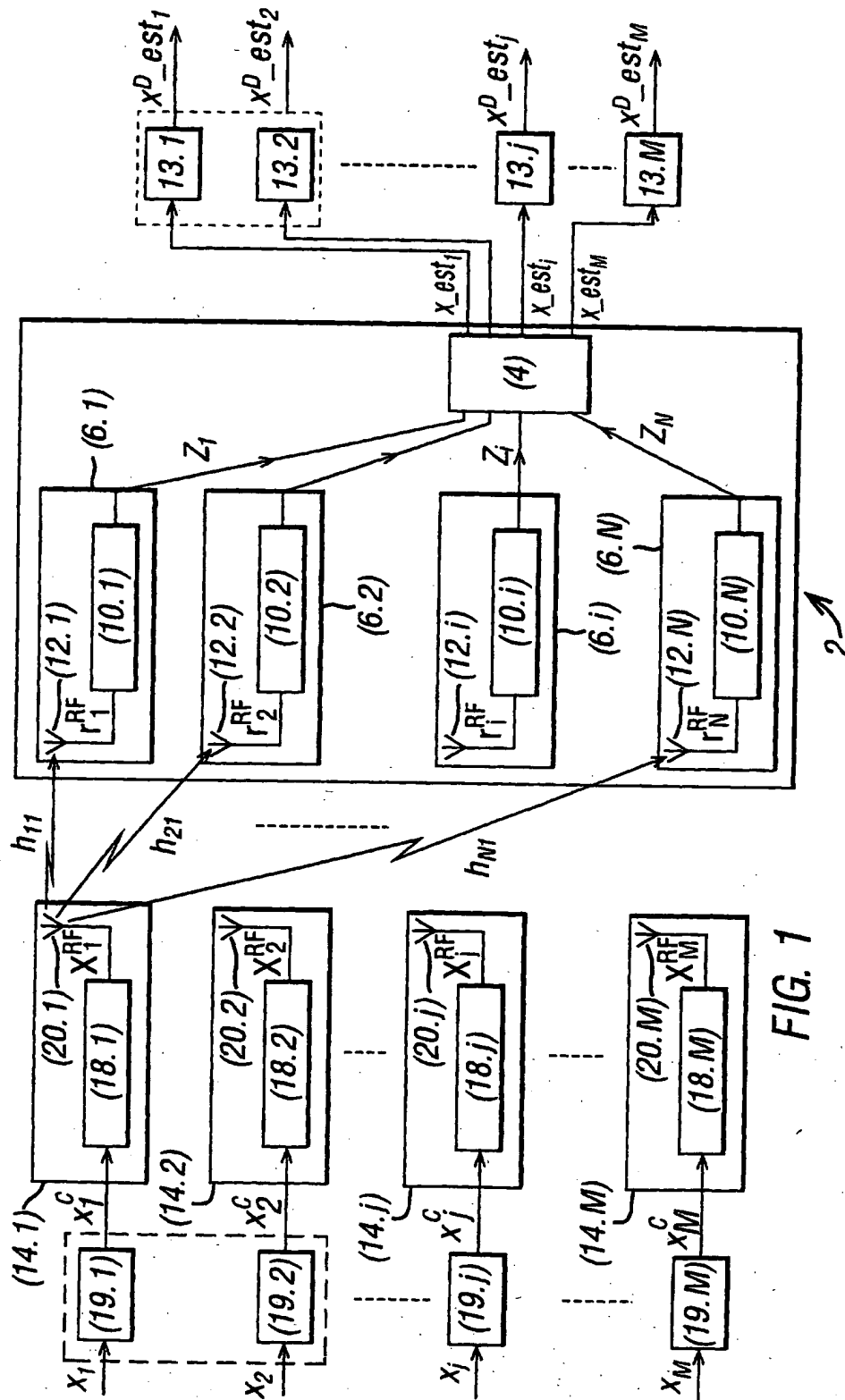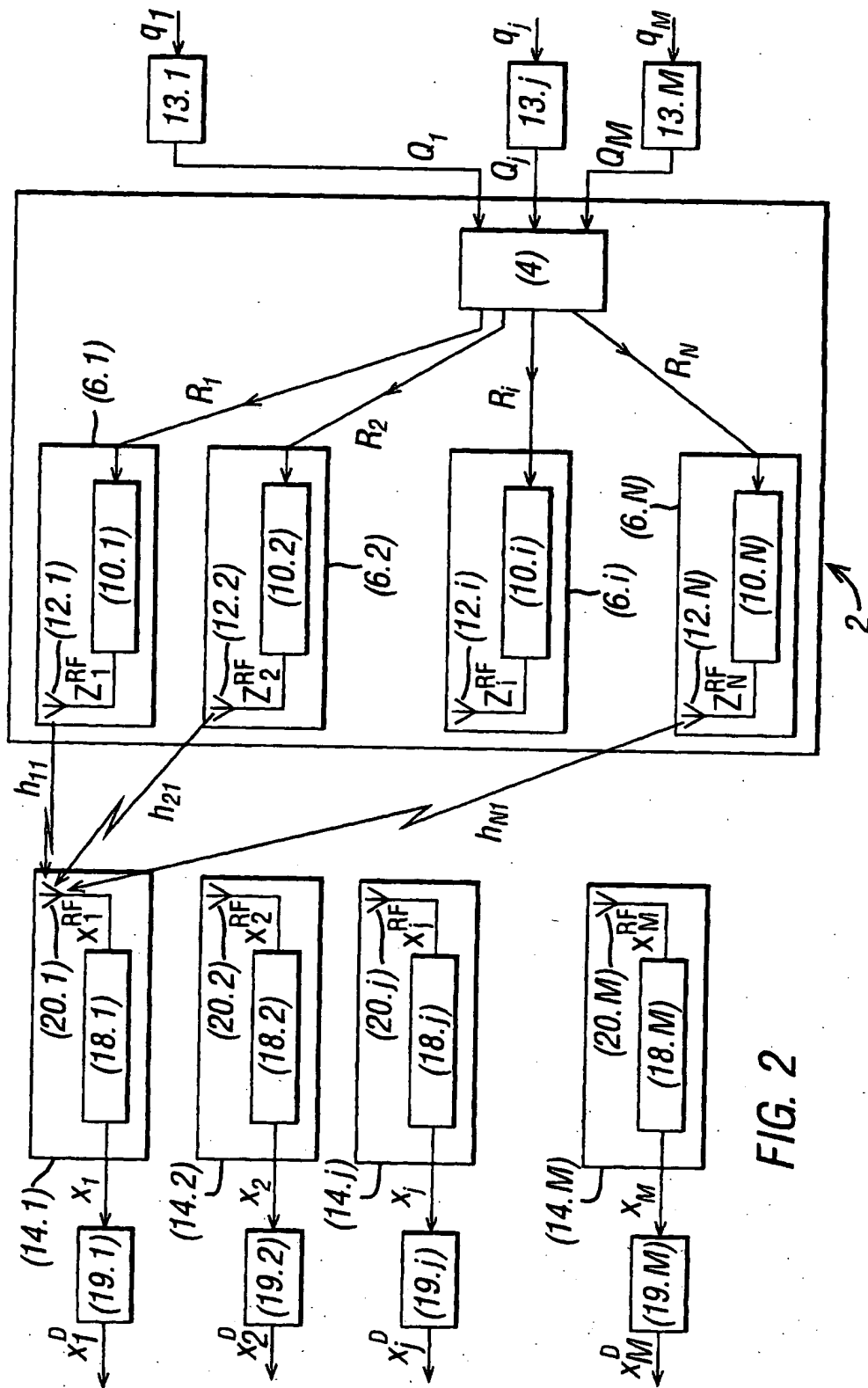
FIG. 1

FIG. 2

FIG. 3

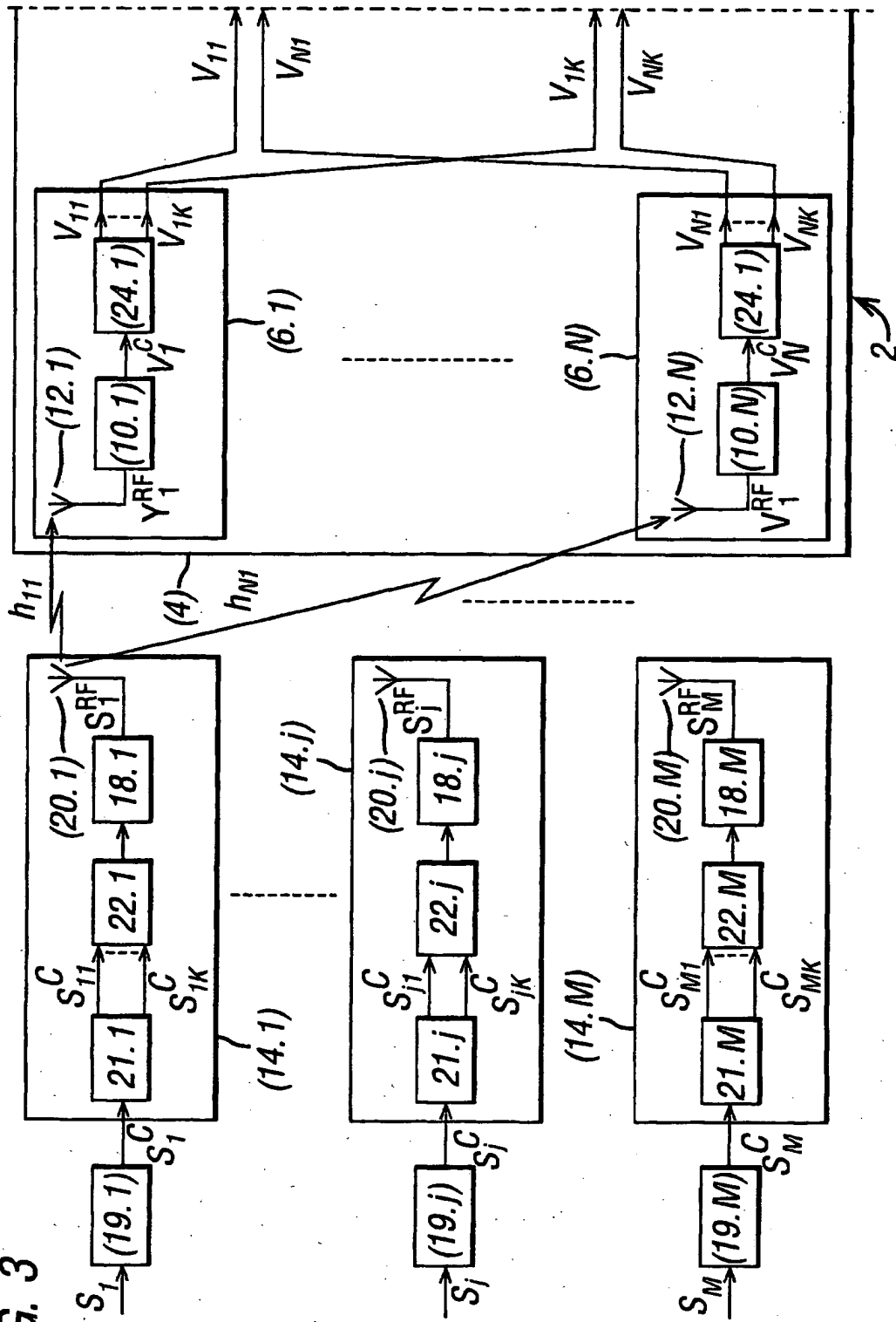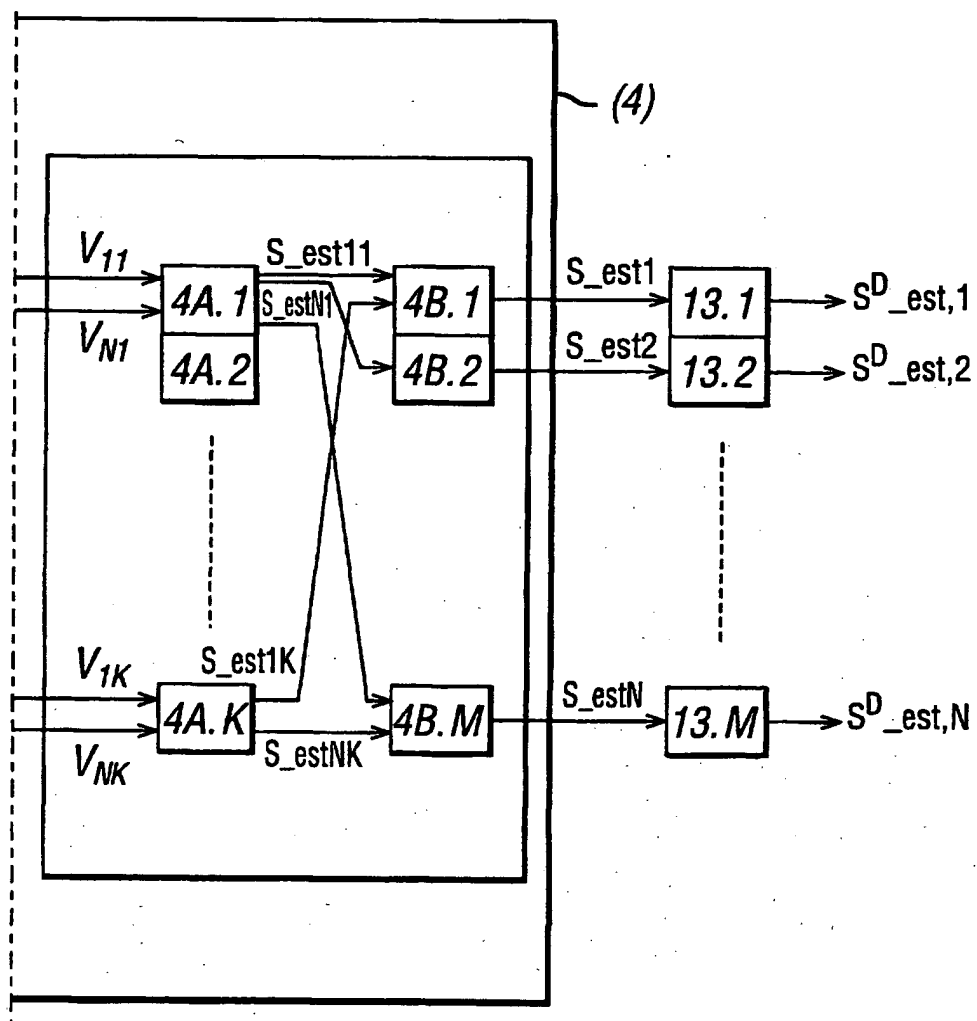## FIG. 3(contd.)

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	10 November 2000	Lustrini, D

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Application Number

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